DESIGN, IMPLEMENTATION AND APPLICATION OF AN ERBIUM-DOPED FIBER LASER FOR THE STUDY OF CANCER CELLS

Final Report

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0. CONTENTS

1. DOCUMENT SCOPE

Design, implementation and application of an erbium-doped fiber laser for the study of cancer cells starts as a continuation of last year's project *Làser de femtosegons en forma de 8 basat en EDFA I controlat per Arduino* carried out by Victor Chausse, Judith Medina, Albert Miguel, Bernat Molas, Joan Sendra i Alfredo Vidal.

The purpose of this project is to design and build a 1550 nm laser based on an Erbium Fiber Amplifier from a 980 nm diode laser pump, amplified in a cavity ring. While the previous project was based on a figure-of-eight non-linear amplifier, the goal of the new one is to design a single-loop amplifier that can ideally be coupled to a pulse generator (external to this project).

Ideally, the latter could be implemented in the ongoing research at IBEC on cell dynamics, especially in cancer cells. Femtoseconds pulses are needed to carry out two-photon excitation microscopy. This is a fluorescence imaging technique that allows a high tissue penetration, which is a very appealing technique for studying living organisms. Basically, two infrared light photons are absorbed for each excitation instead of a single one, allowing the beam to go deeper on the sample while emitting a visible signal.

The project is carried out at the UPC (*Universitat Politècnica de Catalunya*), ETSETB (*Escola Tècnica Superior de Telecomunicacions de Barcelona*) under Jose Antonio Lazaro's supervision. All the necessary materials and clarifications that go beyond the students' resources have been provided.

The project's main objectives are:

- Flawlessly control the current source in order to get an optimum power output of the diode-pumped laser.
- Optimize all erbium-doped fiber parameters to obtain maximum amplifier gain.
- Accurately characterize the final erbium-amplified laser.
- The final and ultimate objective of this project is to design a laser capable of producing femtosecond pulses for a latter application in the study of cancer cell behavior. There is an existing need of a customized laser for such a purpose as opposed to those commercially available.

2. EXECUTIVE SUMMARY

This document provides a detailed account of the design and implementation of an erbium doped fiber laser, currently the most important fiber amplifier in long-range optical fiber communications. The purpose of this report is to ensure that future follow-ups on the development of this laser are done with as small a learning curve as possible. The laser consists of three basic functional components: pumping source, laser cavity (amplification loop and filter) and output.

Firstly, the pumping source was implemented using a diode laser as an optical pump, which is powered by a controllable input current. The control of the input current was carried out using an Arduino Due connected with a voltage-current converter; as such, one can manually specify the desired output current in a user interface and the current will be fed to the laser diode[1]. Secondly, the laser cavity was constructed using an optical fiber loop, with erbium doping as the amplification medium; several other components were included to improve the effectiveness of the system[2]. Among the components is a tunable filter, which is controlled by an additional Arduino to specify a certain wavelength as desired[3]. Lastly, the output is obtained using a WDM 90-10, extracting 10% of the laser intensity in the cavity.

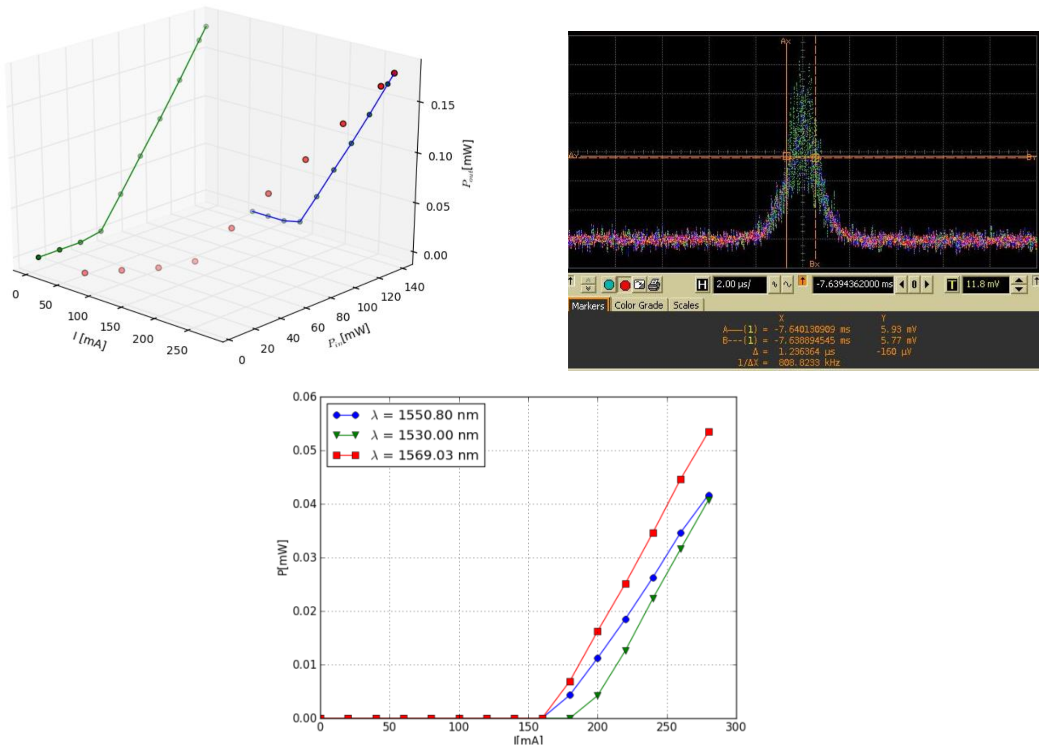

Figure (a) Output power plot as a function of input current and the input diode laser power, *without the tunable filter. (b) Microsecond pulses generated by the laser.* (c) *Power-current characteristic of EDF amplified laser at different peak wavelengths*

Regarding the results, a working and completely controllable laser is obtained, both in cw as well as with the possibility of generating microsecond pulses. These pulses are obtained by modulating the input current at a millisecond rate, which is in accordance with the source's internal clock limitations. Heavy losses are registered; this is easily fixed by fusing the fibers.

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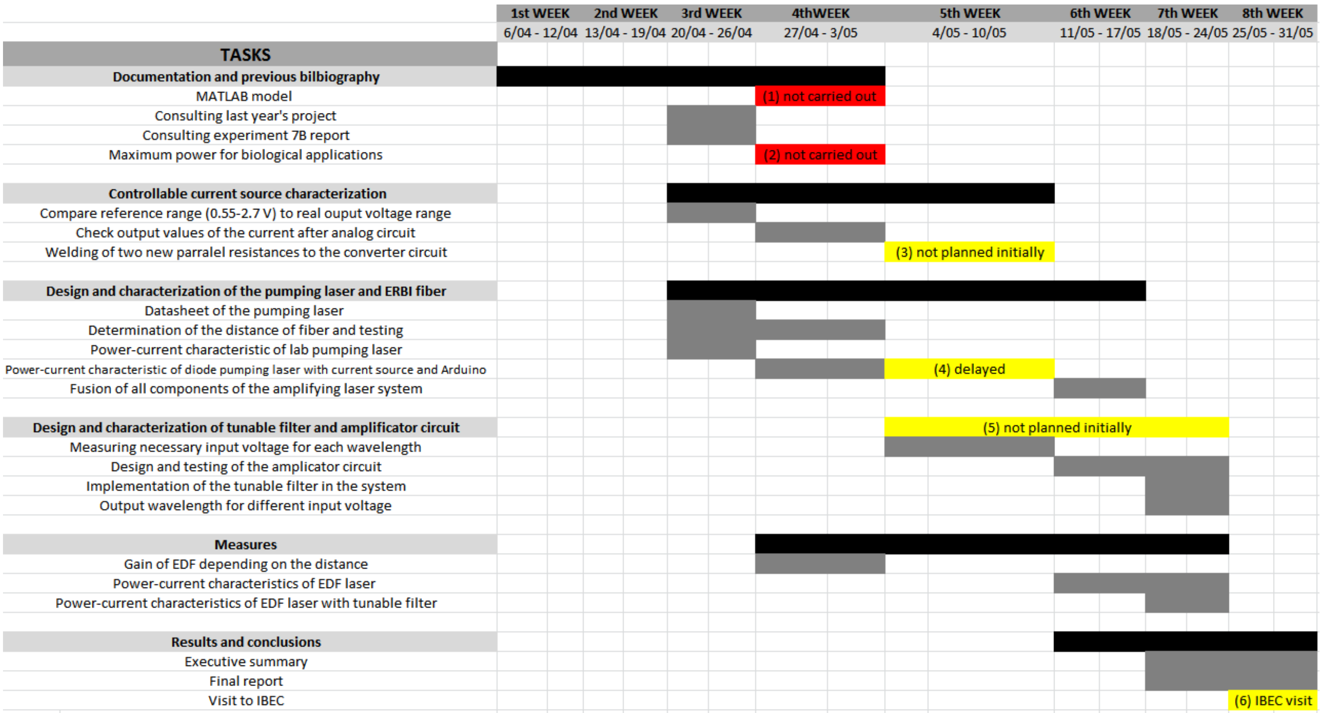
[1] More details regarding the input current – output power of the laser diode are included in 6. System Characterization.
[2] The complete details are in section 4. System Design
[3] The code used to program both Arduino Due's can be found in section

3. TIME PLAN UPDATED



(1) The theoretical model for the optimum erbium fiber length was finally not carried out due to the available fibers at the laboratory. We decided to test experimentally for the adequate length, but for practical reasons only 15m fiber was fused.

(2) Realising the complexity of the project we posponed the focus on the biological application, trying only to get the maximum power out of the laser. The resulting power is very low, so in principle no damage would be done on cellular tissue.

(3) The theoretical value of the maximum output current did not match the experimental one (probably because of the limitations of the digital-analog converter of the microcontroller used), so we decided to change the resistances (R1) of our voltage-current converter in order to increase this value.

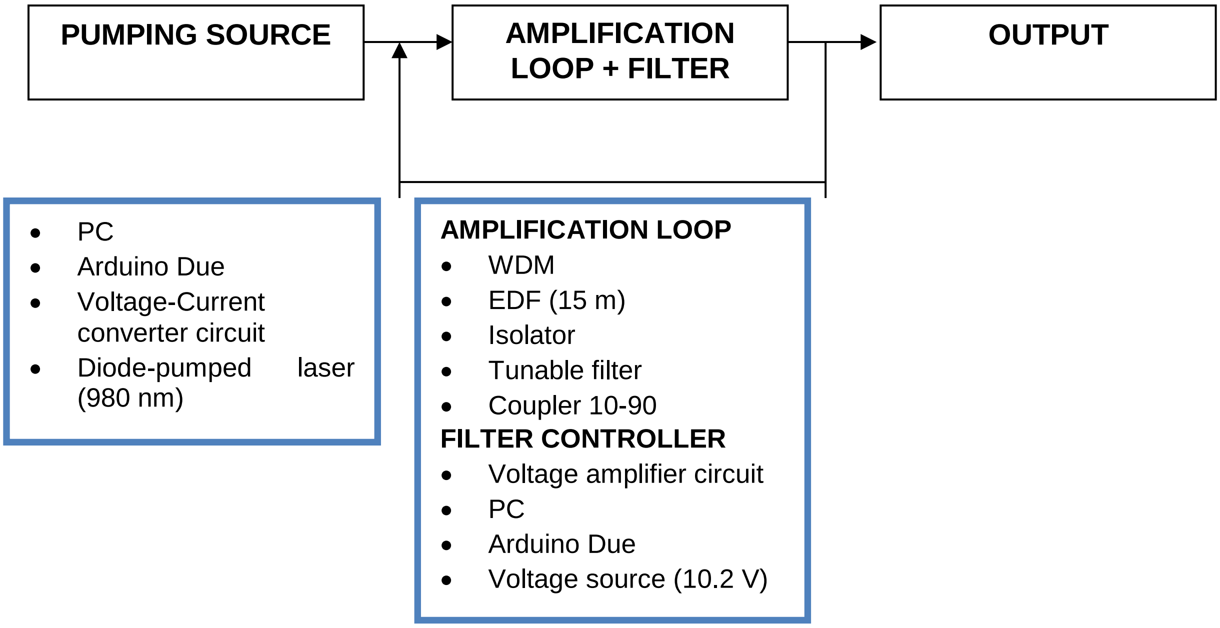
(4) Power-current characteristic was delayed because of the malfunctioning of the voltage-current converter.

(5) The tunable filter was not included in the initial layout of the project (we imagined we would not have enough time to implement it). However, things turned out differently and we finally included and controlled this part.

(6) Visit to the Institute of Bioengineering of Catalonia to get acquainted with biological applications of an Ytterbium-doped laser and other optical techniques.

4. SYSTEM DESIGN DOCUMENTATION

I- SYSTEM BLOCK DIAGRAM



II- ACTIVE COMPONENTS SELECTION AND VALUES

II.1 Erbium-doped fiber

Erbium – doped fiber amplifiers are currently the most important fiber amplifiers in long-range optical fiber communications. They can amplify light in the 1.5 µm region, where telecom fibers have the minimum losses.

Its core is doped with trivalent erbium ions (Er^{3+}) and composes the erbium-doped optical fiber, which is typically a single-mode fiber. Erbium doped fiber laser is a three level configuration laser as far as optical amplifying is concerned (Figure 1). Basically, the electrons are excited to level $^4I_{11/2}$ by the energy of the radiation coming from the diode laser, which is lasing at 980 nm. From level $^4I_{11/2}$ electrons relax by spontaneous emission to level $^4I_{13/2}$ emitting non-radiative energy. Once they are at this level they go down by stimulated emission to level $^4I_{15/2}$ and emit a photon of 1550 nm of wavelength.

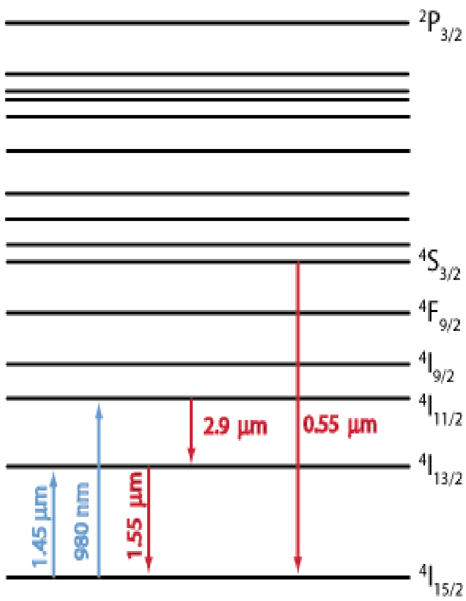


Figure 1 Energy level structure of the trivalent erbium ion and some common optical transitions

It is worthwhile to note that in our case the inverse of population is reached because, as in all lasers, there is a cavity. The particularity of this cavity is that it is not formed by any mirror, it is a ring cavity.

II. 2. Diode laser

The laser used to pump the amplifier is a 980 nm diode laser. Datasheet specifications at 25ºC are given in figure 3.

One of the most important features of a laser is its threshold current, which is the minimum current the diode laser needs to start lasing. This value is approximately 30 mA in our case (see figure 4). The maximum theoretical power is 190 mW for a 330 mA input.

It is also of great significance to know the optical spectra of the laser and its dependence with output power. Figure 3 shows this particular laser is centered at 979.58 nm for 35 mW output and 979.95 nm for 160 mW.

Figure 2 Diode-pumped laser

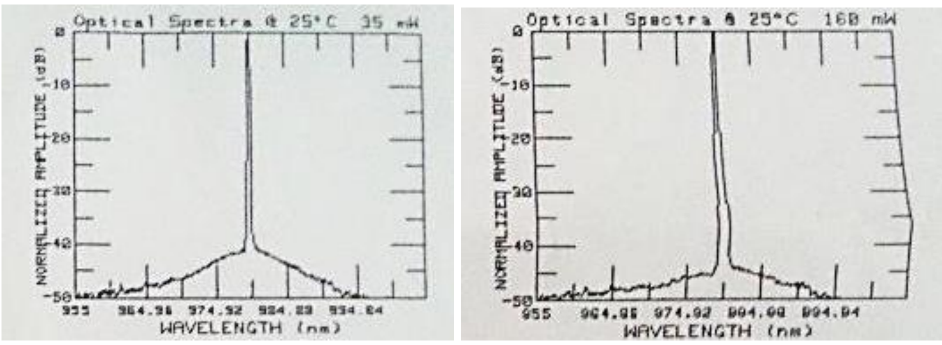


Figure 3 Optical spectra at 25ºC and 35 mW (left) and 160 mW (right) (from datasheet)

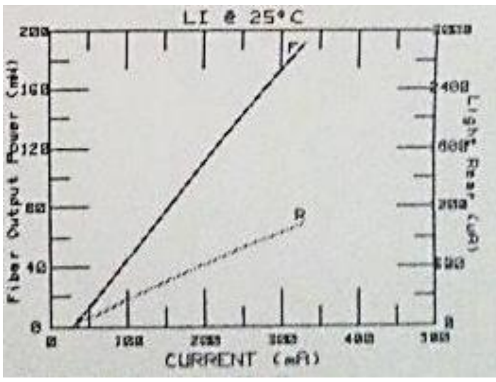


Figure 4 Power-current characteristic at 25ºC (from datasheet)

II.3 – Voltage-current converter

The circuit is designed in order to convert input voltage from Arduino (DAC1) to output current, which will be the input of the diode laser. This input has to be computationally controllable so as to characterize the pumping laser as precisely as possible.

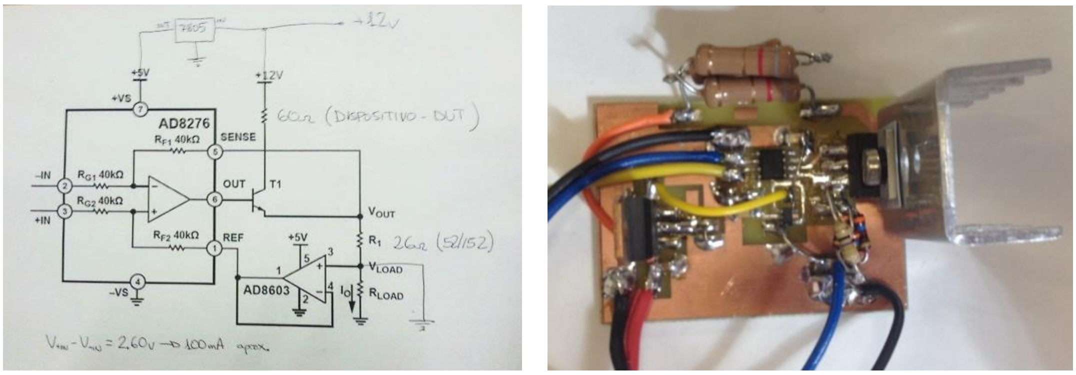


Figure 5 Schematics (left) and experimental implementation (right) of the voltage-current converter

The initial value of R_1 was set at 9Ω (equivalent to four parallel resistances of 36Ω) in order to get an output of 300 mA for a 2.7V input. Further measures showed this value was never reached, deciding to include two new parallel resistances of 39 and 42Ω, setting the equivalent resistance R_1 to 6.32Ω. Consequently, it was possible to get a maximum intensity of 280mA, which was fine in order to prevent possible damages to the diode laser. In order to decide which resistance had to be implemented to get the desired intensity a linear approximation (virtual short-circuit) was taken as valid.

II.4 – Voltage amplifier circuit

The circuit consists on a non-inverting amplifier, controlled with Arduino and designed to amplify the input voltage (limited to 2.7V) in order to reach the range of necessary input voltages of the tunable filter, which is 0-30V. For our purposes, the maximum was set at around 10 V.The circuit follows the schematics:

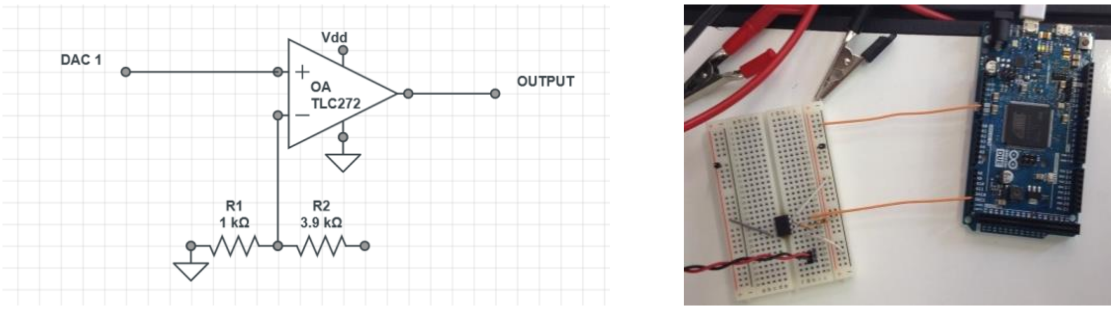


Figure 6 Schematics (left) and experimental implementation (right) of the voltage amplifier circuit

R1 and R2 are ¼ W resistances. The positive supplied voltage V_{dd} fixes the saturable output voltage approximately at 85% of its value. For most of the performances it was fixed to 10.2 V. The gain can be expressed as:

$$G = \frac{R_2}{R_1} + 1 = 4.9$$

which for maximum input 2.7V gives an output of 13.23V for optimum alimentation conditions. Obviously, this value could never be reached so the amplifier saturated.

I.5 – Tunable filter

The tunable filter was later included in the project. The initial idea was to manipulate an optical filter in order to assure the amplified signal was centered at 1550 nm. However, it seemed of great interest to use a tunable filter instead, controlled with voltage, so as to sweep a range of wavelengths instead of only one.

Figure 7 Voltage-tunable filter

II.6 – WDM, isolator and coupler

These three components are essential for the cavity to work efficiently. The isolator's main function is to allow the transmission of light in only one direction, preventing unwanted feedback into the cavity and destructive interference. As for the Wavelength Division Multiplexer, it allows to combine multiple signals at different wavelengths for transmission along a single fiber. This particular WDM has 980 and 1550 nm inputs for a single output. Finally, the coupler (90-10) is the key element to close the loop while getting an output from it: the 90% fiber is included in the cavity and the 10% end is the output of the device.

III- SOFTWARE TOOLS

In order to be able to control both the current source and the tunable filter, two Arduino Due boards were used. The software used to control them is the derivation of the C programming language used by Arduino.

IV- SOFTWARE BLOCKS

The software used in this project can be classified into three main blocks:

- Continuous pumping of the diode laser
- Pulsed pumping of the diode laser
- Amplifier circuit control

5. SYSTEM IMPLEMENTATION DOCUMENTATION

I- FINAL SCHEMATICS

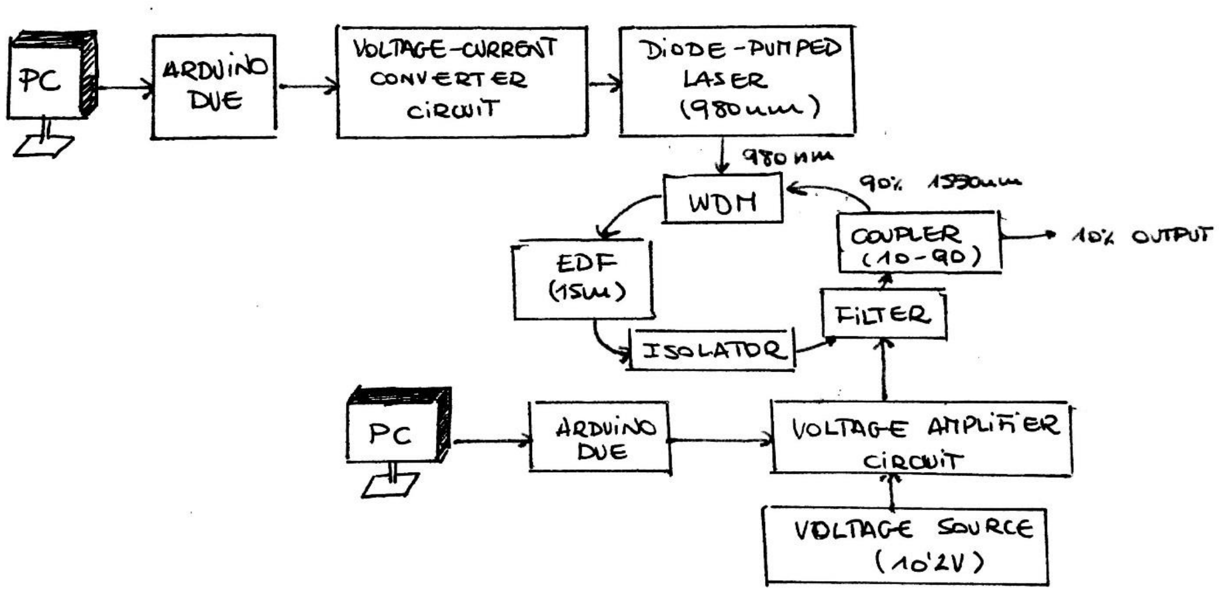


Figure 8 Hand-made final schematics of the project

II- CIRCUIT PICTURES

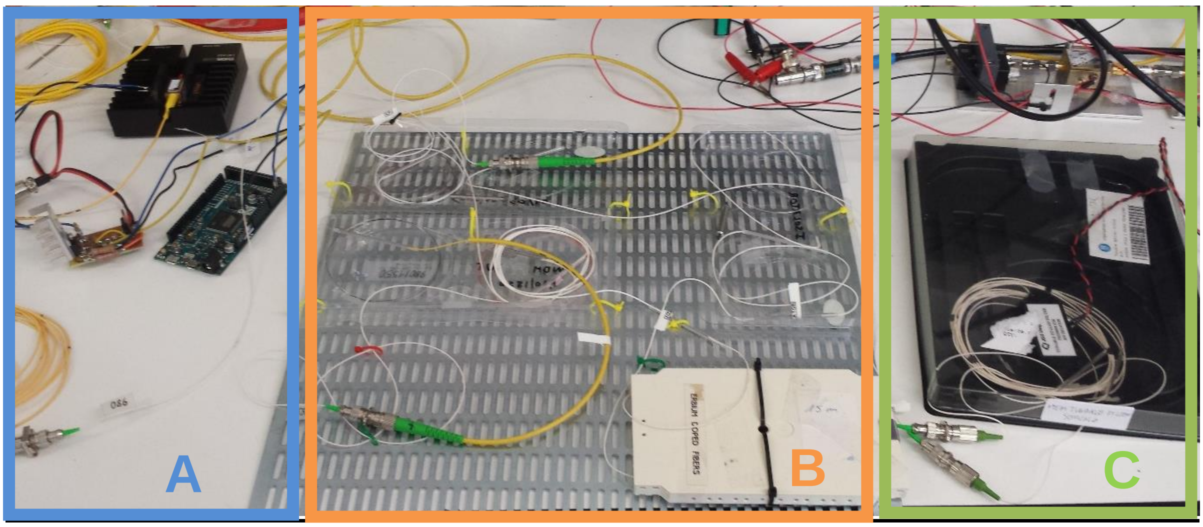


Figure 9 Picture of the real implementation of the project. A: Pumping Source. B: Amplification loop. C: Voltage-tunable filter.

A.- Pumping Source

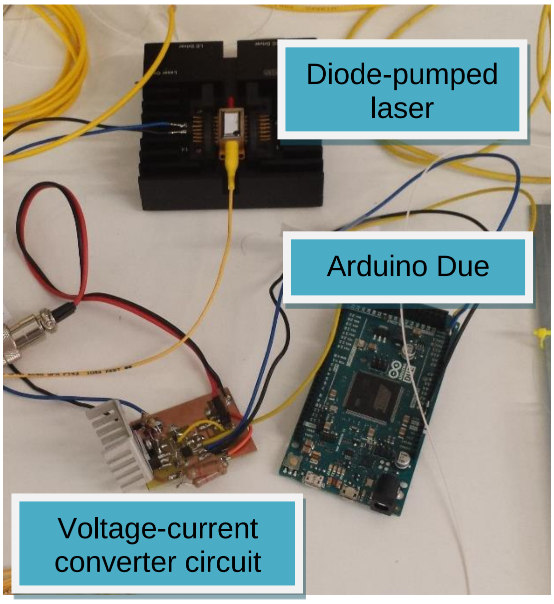


Figure 10 Real implementation of the pumping source

The PC is connected to the Arduino Due using an USB - microUSB cable. The Arduino Due is linked with the Diode-Pumped laser which introduces photons at 980 nm to the loop through the WDM input 980 nm.

B.- Amplification loop

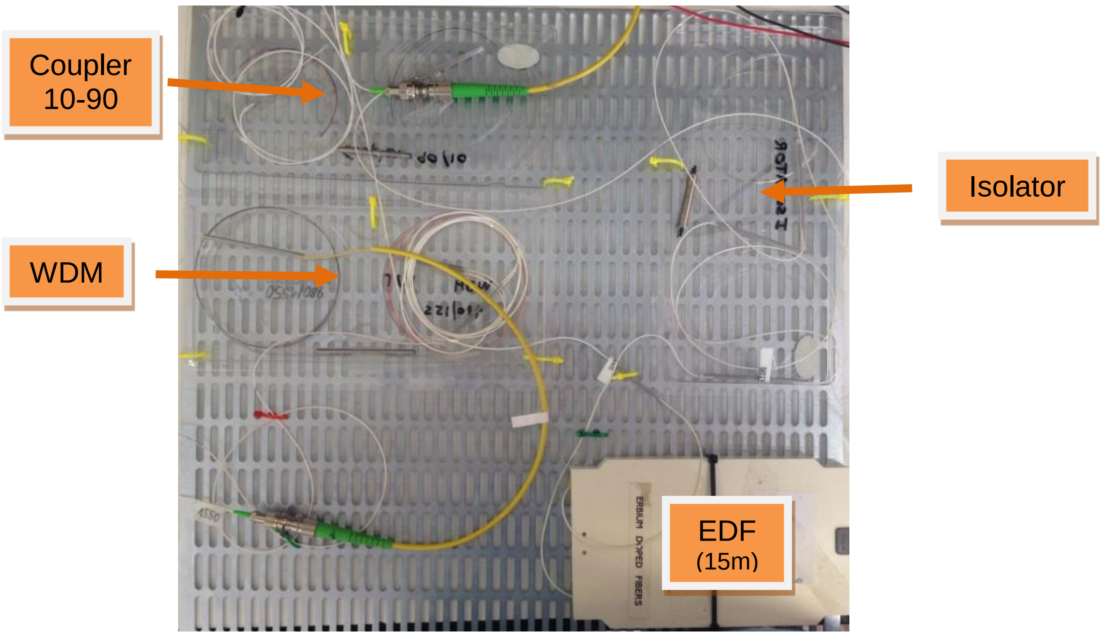


Figure 11 Amplification loop and its components

Some fibers have been fused to decrease the loss (dB) due to the connectors. The junctions fused are WDM output - EDF, EDF - Isolator and Coupler 90 – WDM input 1550 nm. The filter has not been fused because of its high cost, so it can be used in other projects. In order to increase the power at the output of the Erbium-doped fiber laser, all the fibers should be fused.

The components have been fixed in the plate with cable ties.

C.- Filter Circuit

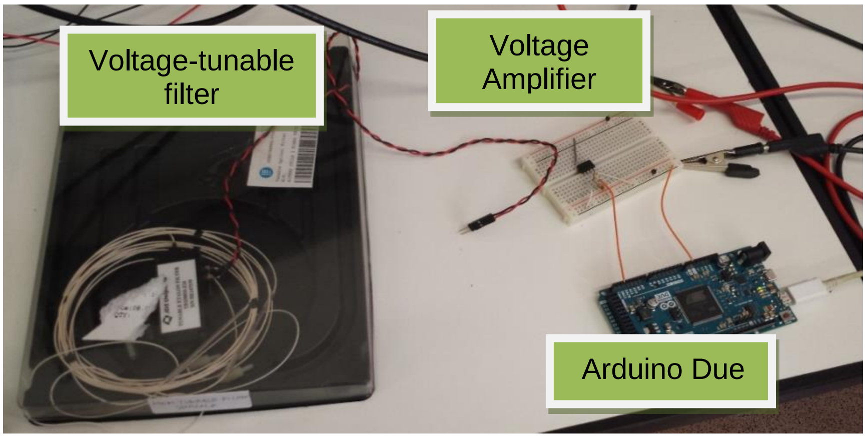


Figure 12 Filter circuit

The PC is united to the Arduino Due using an USB - microUSB cable. The Arduino Due is joined with the Voltage amplifier circuit, which is powered by a voltage source at 10.2 V, and this one to the filter. Finally, the filter is connected to the main loop between the isolator and the coupler.

All three parts have been introduced and fixed in a box, so the Erbium-doped fiber laser can be easily transported.

III- ALGORITHMS

III.1 – Script to control the current source

It allows to set the intensity at the desired value (from 0 mA to 280 mA) just by introducing it at the Serial Monitor. Both the intensity and the voltage (quantified by levels (8-bits) from 0 to 255 corresponding to 0.5 and 2.7V linearly) will appear on the Serial Monitor after introducing a particular intensity.

codigolaserbombeo

```
const int pinsalida=DAC1;
void setup() {
  Serial.begin(9600);
  pinMode(pinsalida,OUTPUT);
  analogWrite(DAC0,0);
}
void loop() {
  while (Serial.available()>0) {
    //busca el proximo entero del monitor serial
    int i = Serial.parseInt();
    if(Serial.read () == '\n') {
      //limita los valores a que esten entre 0 y 255
      i=constrain(i,0,280);
      //conversión voltaje-intensidad
```

```
      float v=i*(255.0/280.0);
      //redondeamos intensidad para
      v=(int)round(v);
      //manda el voltaje que queremos al pin de salida
      analogWrite(pinsalida,v);
      //escribe el voltaje que te he dado
      Serial.print("intensidad:");
      Serial.println(i,DEC);
      Serial.print("voltaje:");
      Serial.println(v,DEC);
    }
  }
}
```

III.2 – Script to control the tunable filter

It has the same structure as the one for the current source. It allows introducing a value for the output voltage from the Serial Monitor. The possible values also go from 0 to 255. A possible improvement for this algorithm would be to directly input the desired voltage instead of its quantified level.

```
filtro_sinto
  Serial.begin(9600);
  pinMode(pinsalida,OUTPUT);
}
void loop() {
  while (Serial.available()>0) {
    //busca el proximo entero del monitor serial
    int v = Serial.parseInt();
    if(Serial.read () == '\n') {
      //limita los valores a que esten entre 0 y 255
      v=constrain(v,0,255);
      analogWrite(pinsalida,v);
      //escribe el voltaje que te he dado

      Serial.print("voltaje:");
      Serial.println(v,DEC);
    }
  }
}
```

III.3 – Script to generate pulses:

This script sets the intensity at 0 mA (0.5 V) (LOW) for a certain time and then raises the intensity to 280 mA (2.7 V) (HIGH) for another period of time in each loop. Both lapses of time can be modified independently with the order *delayMicroseconds*() as desired. Therefore, this script can be used instead of script *codigolaserbombeo* (III.1) in order to generate pulses at the output of the erbium-doped fiber laser. The LOW and HIGH durations give different results, as will be explained later in this document.

codigolaserpulsos

```
const int pinsalida=DAC1;
int v = 255;
unsigned long previousMicros = 0;
unsigned long currentMicros;
void setup() {
  // put your setup code here, to run once:
  Serial.begin(9600);
  pinMode(pinsalida,OUTPUT);
  analogWrite(DAC0,0);
}

void loop() {
  // put your main code here, to run repeatedly:
   analogWrite(DAC1,0);
   //para delays mas cortos ponemos delayMicroseconds()
   delayMicroseconds(500);
   analogWrite(DAC1,v);
   delayMicroseconds(100);
}
```

6. SYSTEM CHARACTERIZATION

I- MEASUREMENT SET-UP

All measurements were performed with the laboratory instruments, including:

- Oscilloscope (Agilent Infiniium 54854A DSO with a 4GHz bandwidth)
- Power supply (Promax FAC-662)
- Spectrometer (EXFO FTB-400)
- Multimeters
- Powermeters

II- FINAL COMPONENTS MEASUREMENT GRAPHS AND RESULTS

II.1. Voltage-current converter circuit

Since the voltage supplied by the Arduino does not get to zero when settled to the zero level, we decided to get the difference of voltage from DAC1 and DAC0, so that when both were at the zero level the difference of voltage would be zero. This is important in order to be able to turn off the laser without having to disconnect it from the Arduino. However, surprisingly, we found that at level zero, both DACs did not have the same voltage; there was a difference of 10 mV. Fortunately, the current supplied by the current source with this voltage did not reach the threshold current for the laser; therefore, it did not lase.

Bearing this in mind, the input of the algorithm is a scalar level between 0 and 255 quantizing output voltages from 0.54V to 2.74V. All intermediate outputs are obtained by a linear relation with the input level.

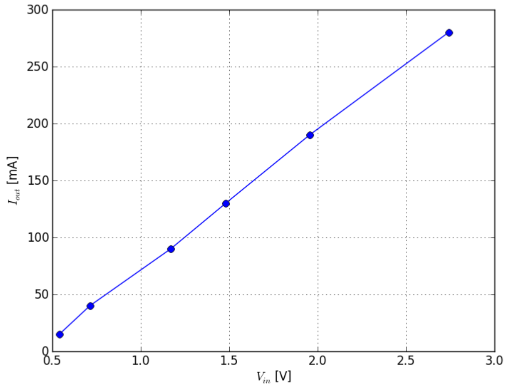


Figure 13 Input/Output of the voltage-current converter circuit for R1=6.32Ω

Maximum output current for different values of of R_1 are summarized in the following table, being the 6.32Ω the final value of the resistance:

R_1 (Ω)	I_{max} (mA)
9	180
6.32	280

Table 1 Output current values for different R1

II.2. Diode pumping laser

Once the output of the voltage-current converter controlled, the output power of the diode laser was characterized for varying input current from 0 mA to the maximum 280 mA obtained. Measurements were repeated for different reference wavelengths of the powermeter. As 980 nm was not one of them, results for this particular wavelength were interpolated from the 1300 and 850 nm data assuming a linear dependance.

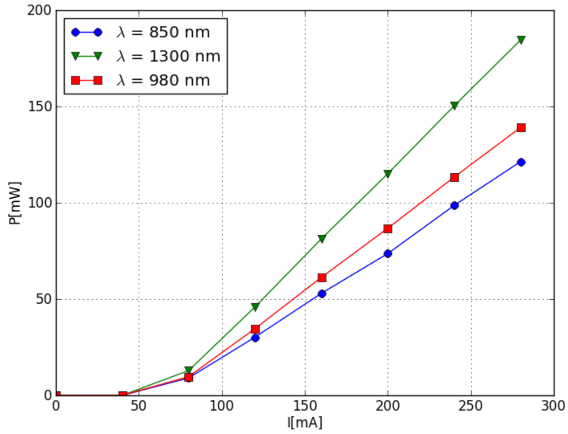


Figure 14 Power-current characteristic of the diode pumping laser

The measured output power for 980 nm was lower than the theoretical maximum 190 mW output power for maximum 330 mA input current (values from datasheet), as the extrapolated value for a 330 mA input would be 171.4 mW (imposing a linear dependence once exceeded the threshold current). Moreover, this output was unreachable with the actual voltage-current converter.

II.3. Voltage amplificator circuit

Output voltages were measured for inputs going from 0.5 to 2.7V. The measures were repeated for 15 and 11V alimentation voltage, obtaining a non saturated and a saturated output respectively.

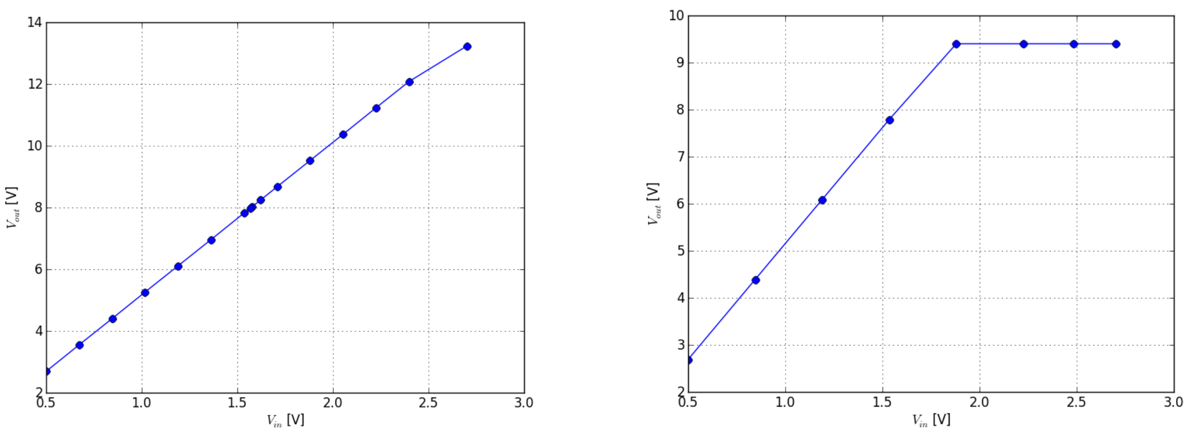


Figure 15 Input/Output of the voltage amplifier circuit for Vdd=15V (left) and Vdd=11V (right).

Optimal configuration was with V_{dd} fixed at 15V in order to obtain a wide range of output wavelengths of the filter. However, experimental implementation of the operational amplifier turned out being problematic (possibly because maximum input current of the OA was exceeded). Lowering of the alimentation voltage down to 11V solved this problem, but limited the range of output wavelengths.

II.4. Erbium Doped Fibers

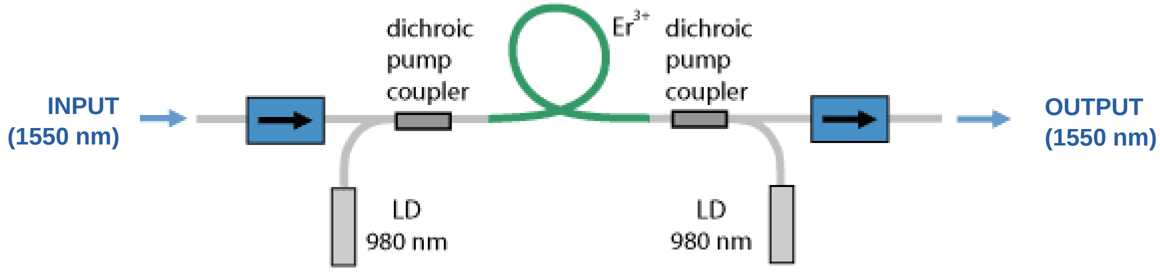


Figure 16 Schematic set-up for gain measurements of a simple erbium-doped fiber amplifier

The gain was calculated as the difference between the output of the 1550 nm ending of the MPX and the input power of the 1550 nm laser in dBm. Data in table 2 was measured fixing the reference wavelength of the powermeter to 1300 nm.

Low signal input				
EDF length (m)	5	10	15	20
Gain (dB)	20.7	29.18	31.04	32.09
High signal input				
EDF length (m)	5	10	15	20
Gain (dB)	6.18	11.39	12.24	12.82

Table 2 Gain measurements for low (-22.9 dBm input power) and high (0.5 dBm input power) signal

Results show the 20m fiber has the maximum gain in both cases and do not match last year's. This fiber was particularly characterized by measuring the gain as a function of the input power.

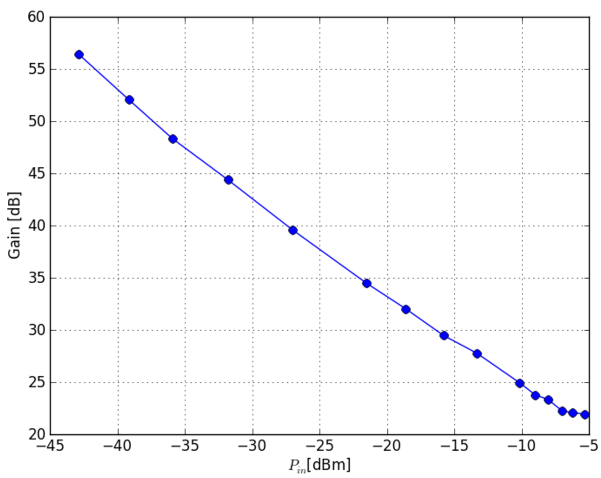


Figure 20 m EDF gain for variable input power

III- MEASUREMENT GRAPHS AND RESULTS. FINAL PERFORMANCE

III.1. Tunable filter

Measures were performed with V_{dd}=10.2V and maximum 280 mA input current supplied to the pumping diode laser. The output saturates at 8.75V due to the margin fixed by the input voltage V_{dd}.

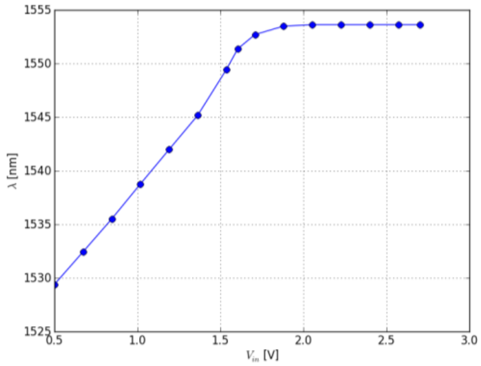


Figure 17 Output wavelength of the tunable filter for varying input Arduino voltage

With this configuration, output wavelengths go from 1529.4 to 1553.62 nm. 1550 nm is contained in this range; this result was foreseeable as 8V is below the saturation voltage.

III.2. EDF amplified laser

a) Laser gain

In Figure 18, there are threshold currents and input power for the diode laser and erbium doped fiber respectively.

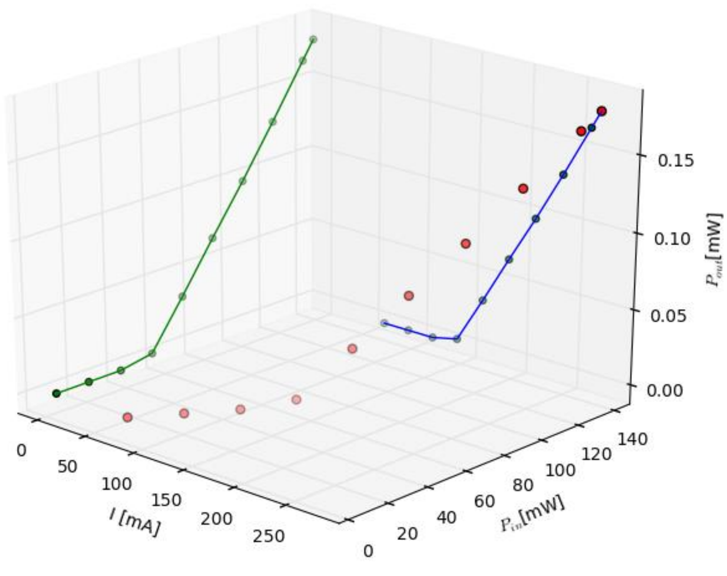


Figure 18 (Red dots) Output power plot as a function of input current and the input diode laser power, without the tunable filter. The green and blue lines are the projections of the red dots in the horizontal planes.

From the data shown in Figure 18 (green line), it can be concluded that all the power is lost for $Pin < 60\ mW$ and for $P_{in} \in [60{,}140]mW$ the losses are around -29.7 dB. As it has been said, this huge loss of power is due to the burned fiber between the diode laser and the rest of the loop.

b) Power-current characteristic

In order to completely characterize the laser, power-current characteristics were measured for different wavelengths using the tunable filter and the corresponding input voltage. As shown in figure 19, the threshold current seems to depend on this wavelength, as it decreases for increasing values of λ. On the contrary, the slope does not seem to vary excessively. Output power is extremely low, as mentioned in the previous section, even more when compared to the output power of the diode laser which was around 160 mW.

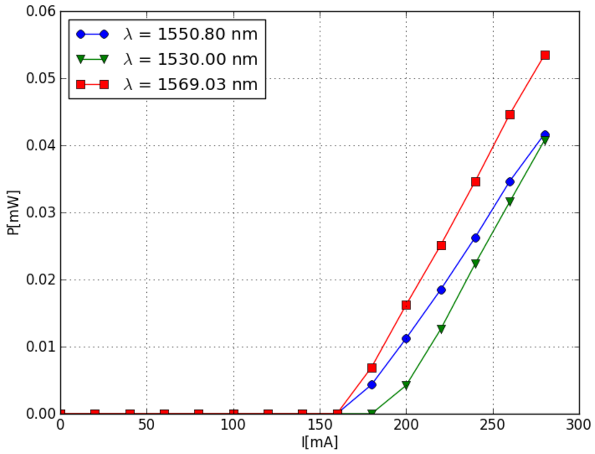


Figure 19 Power-current characteristic of EDF amplified laser with tunable filter settled at different peak wavelengths

c) Optical spectra of the laser

The output of the coupler can be connected to the spectrometer in order to observe the optical spectrum of emission of the EDF laser. Figure 20 shows these results for different set-up configurations. Spectrum on the left is the laser emission when no tunable filter is included, and shows that the experimental wavelength emission is 1570 nm and not the theoretical 1550 nm. Figure on the right is the display for the EDF laser emission including the tunable filter set for a 1550 nm output. Not only the tunable filter really gets to shift the output wavelength, but it also makes the spectrum sharper and more like the ideal emission spectrum of a monochromatic laser.

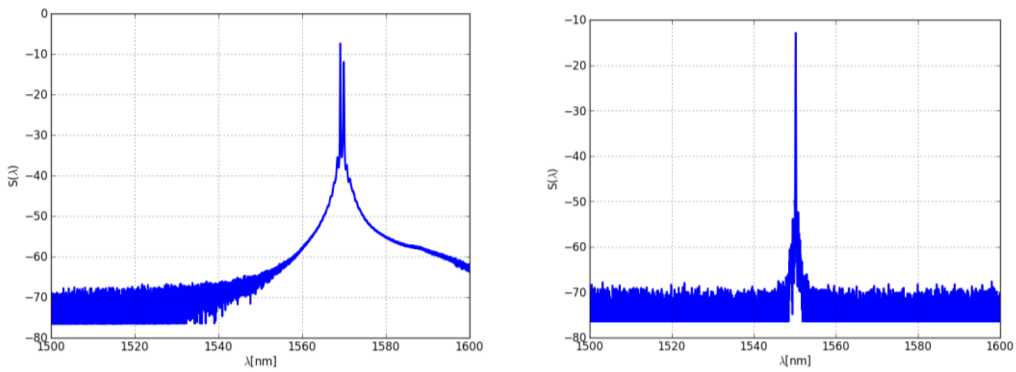


Figure 20 Optical spectra of EDF laser without tunable filter (left) and with the filter set at 1550 nm (right)

III.3. Pulses

a) <u>Features of the programmed pulses</u>

The pulses were programmed with Arduino by turning on and off the input pumping with the algorithm presented previously. Different periods and duty cycles were tested, leading to some errors due to the limited time of response of the Arduino. The shortest pulses that have been produced have periods of the order of 100 µs.

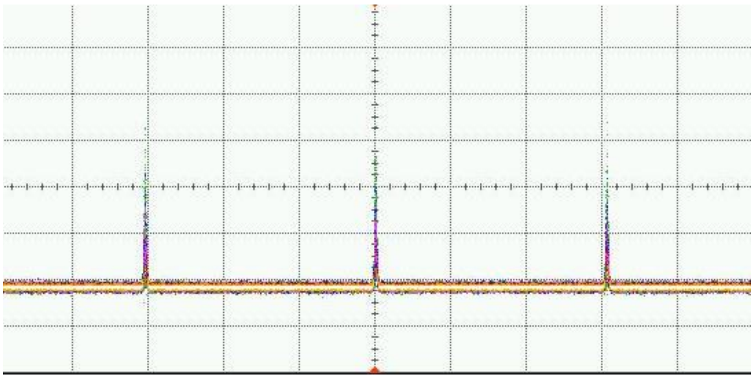


Figure 21 600 µs pulses (500 down 100 up)

Regarding the settling time of these pulses, as can be observed in Figure 22, it is longer than the pulse duration but of the same order of magnitude. It is similar to the response of a second order transfer function with two complex poles; this transfer function models the behavior of the entire laser system.

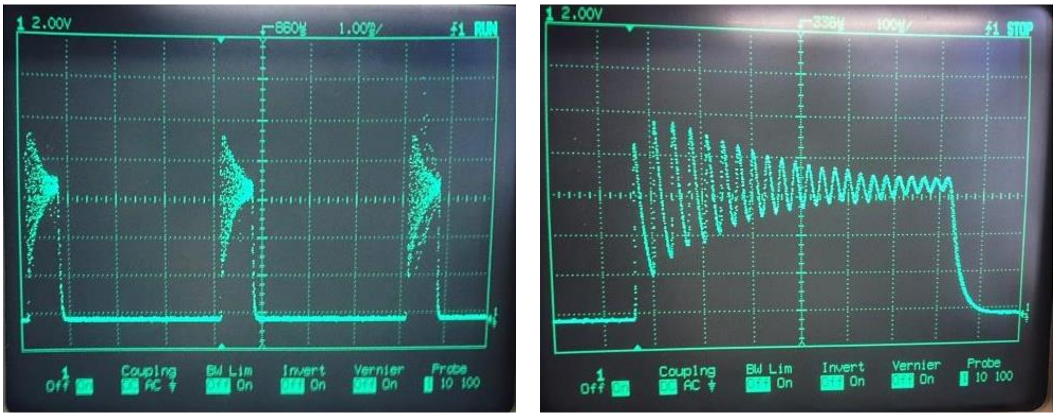


Figure 22 4 ms pulses with 25% duty cycle (el de la derecha ampliado)

b) <u>Secondary pulses</u>

As shown in the pictures, when ordering the Arduino to produce pulses of about 100µs of period just by switching on and off the pumping, other Gaussian-like shaped pulses appeared during the on stage. The pulses in the following figures come from 4 ms pulses with 25% duty cycle.

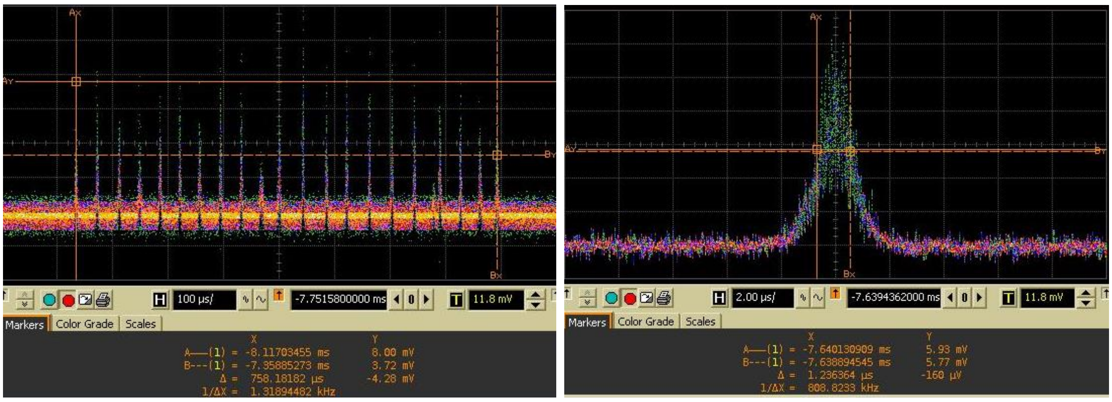


Figure 23 Secondary pulses zoomed (right) and for an entire principal pulse (left) for 4ms and 25% duty cycle Arduino-controlled pulses

The period of the secondary pulses was measured making the average of 20 periods with a total time of 750µs, which represents a period of roughly 38µs for each pulse. As for the time width, figure on the right shows they have a duration of roughly 3 µs, which is much less than those sent by the Arduino.

IV- SHORT DISCUSSION

IV.1 – About the optical spectrum of the EDF laser

Results are very satisfying as far as the monochromaticity of the laser is concerned. However, it was surprising to notice that when no filter is implemented, the peak of emission was centered at 1570 nm rather than at 1550 nm as expected. This shift in the wavelength could be attributed to imperfections in the fiber or in the doping, as well as cavity resonance effects (length of the loop).

IV.2 - About the secondary pulses

There are many things to clarify about the pulses produced from the Arduino. As commented in the previous section, secondary Gaussian pulses appeared during the HIGH stages of programmed pulses. There are two main reasons for this phenomenon to happen.

The first one is that the system has a very intense transient response, since when the pump was continuous, the output was continuous too. As seen in figure 22, the fact that the Arduino pulses have a large settling time, almost as long as the desired period, and a high overshoot also contributes this phenomenon to appear.

The second hypothesis is attributing this pulsed behaviour to the travelling time of the beam inside the cavity ring. Considering there are about 100 m of optical fiber in the cavity (adding the length of the EDF, the WDM, the coupler, the isolator and other fibers) and assuming the light travels at $v = cn_{core}$ (with an average 1.5 refractive index), the lapse time inside the loop is of the order of microseconds, which approximately matches the temporal width of the secondary pulses. This hypothesis is even more consistent when comparing these results with the continuous ones, where no secondary pulses are observed. Logically, when the pumping is continuous there are no off-stages of the laser and even if there was a secondary pulse corresponding to each loop of the cavity it would not be noteworthy in the final optical spectrum.

In spite of the appearance of this phenomenon, it is worth saying that it is highly convenient, so it allows to obtain shorter pulses without the need of implementing any complementary set-up. On the other hand, the laser's behavior becomes more unstable, as the pulses are not the same throughout time.

7. CONCLUSIONS

Finally, it has been possible to design, implement, control and characterize an erbium-doped fiber laser, with the possibility to lase in cw or in microsecond pulses. The wavelength can be adjusted with a tunable filter controlled by an external voltage source. As for the bandwidth of emission of the laser, it is surprisingly narrow, therefore, the laser can be considered monochromatic; this characteristic is further assured with the use of the filter.

The control of the supply current for the laser diode as well as of the voltage for the tunable filter was carried out effectively using Arduino Due's, which proved to be very useful in being able to input precise values at command. Notwithstanding, regarding the efficiency of the laser, heavy losses are registered probably due to faulty connectors. In fact, it was later noticed that the end of the pumping laser fiber had been burned due to the excess of input power causing many of the power losses in the system. Successfully fusing the fibers would solve this problem.

It was not possible to use this first prototype for the study of cancer cells, as there is a need for much shorter pulses (of the order of femtoseconds) in order to get high resolution images both in space and time, as well as an increase of the output power. It was made clear to us that pulses of such duration would only be achieved through mode-locking, a possibility to consider for future implementations.

8. REFLECTION DOCUMENT

This is a rather ambitious project considering the short time students have to carry it out. Many considerations or models were neglected for practical reasons, relying on experimental results instead. More accurate calculations would have certainly predicted several of the problems found along the project and would have provided a solution.

This project gave us a good idea of what experimental laboratories are really like; things do not always turn out as predicted since some measurements can be wrong just because of the instruments or one might have to spend a whole session understanding how a device works. A good work plan is crucial in order to finish before the deadline.

It is also very motivating to know what the laser's applications are, and only when visiting IBEC are these made clear. However, it is interesting to see commercial instruments, being already familiar with optical devices, in particular, with fiber-doped lasers.

If this project is continued next year, there are some basic improvements that would have to be done:

- Fusing all fibers in order to avoid any connector losses. They are the most probable cause of power loss.

- Producing pulses with mode-locking rather than by turning on and off the pumping voltage with Arduino. Duration of the pulses could be decreased by several orders of magnitudes using this method.